Biomechanical Beam Analysis of Long Bones From a Late 18th Century Slave Cemetery in Cape Town, South Africa

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ABSTRACT This study aims to quantify the physical demands of a sample of late 18th century skeletons from an unmarked burial site on Cobern Street, Cape Town, South Africa. Historical studies suggest that these individuals were either slaves or "free black" people of low socioeconomic standing. Cortical cross-sectional areas of paired humeri and tibiae from the Cobern Street collection (N = 29), a modern cadaver collection (N = 31), and a hunter-gatherer collection (N = 30) were compared by means of biomechanical beam analysis on computerized tomography scans. Results showed that the Cobern Street sample, both males and females, were closer to the modern group in total tibial cortical area and in the second moments and polar moments of cortical area, than to the hunter-gatherer group. It is assumed that these results can be explained by differences in lower limb activity. Tibial strength properties showed the hunter-gatherer peoples to be highly mobile and active walkers in comparison to the Cobern Street and modern samples. The males from the Cobern Street sample showed significantly higher values for humeral strength properties than either the hunter-gatherer or modern individuals, attesting to their status as manual laborers. The humeral cross-sectional strength properties for females were very similar between the Cobern Street and modern groups but again significantly different from the hunter-gatherer sample. The domestic chores performed by females of the recent cadaver sample may be very similar to those performed by the Cobern Street sample. Am J Phys Anthropol 112:207–216, 2000.

In September 1994, a historic burial ground on Cobern Street (Cape Town, South Africa) was discovered during construction work. Although the site is not recorded as a cemetery, archival information and evidence from associated grave goods (Apollonio, 1997) identify these graves as the remains of late 18th century people of low socioeconomic standing, in ground allocated for the use of the slave and the "free-black" peoples of Cape Town (Morris, 1997). Historical records show that the most common geographic origins of these slaves were Madagascar, the East African Coast, India, and Indonesia (Armstrong and Worden, 1989). However, very little is known about the biology of these people. Thus the skeletal remains excavated from the Cobern Street site represent a unique record of this segment of the Cape Town community. A preliminary investigation of this skeletal collection has

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TABLE 1. Sample size, sex distribution and age

	Male		Female		Combined	
	N	Age (years) mean ± SD	N	Age (years) mean ± SD	N	Age (years) mean ± SD
Modern sample[1]	18	59.4 ± 14*	13	59.8 ± 17*	31	59.6 ± 15*
Cobern Street[2]	18	36.5 ± 8	11	37.8 ± 10	29	36.1 ± 8
Hunter-gatherer[3]	15	31 ± 12	15	32 ± 9	30	31 ± 11

[1] Sex obtained from University of Capetown cadaver records.
[2] Sex and age determination by Constant and Louw (1997).
[3] Sex and age determined by the authors as described by Constant and Louw (1997).
* $P < 0.05$.

shown extensive evidence of osteoarthritis and trauma, suggestive of a physically demanding lifestyle (Holtzhausen and Slater, 1997).

This study aims to more accurately quantify the physical demands (type and level of activity) of this group, by comparing the strength of their long bones with that of two comparison groups: a modern sample and a hunter-gatherer sample. The authors hypothesize that the Cobern Street people lived a more physically demanding lifestyle than the comparison groups.

The method of biomechanical beam analysis described by Ruff (1992) is used in this study to compare the type and level of activities among these three samples. Mechanical bone stress and strain developed under loading influence the amount and distribution of cortical bone in cross sections of long bones (Chamay and Tschantz, 1972; Lanyon and Baggott, 1976; Jones et al., 1977; Goodship et al., 1979; Lanyon et al., 1979; Woo et al., 1981; Lanyon, 1982; Rubin and Lanyon, 1984). From the amount and distribution of cortical bone, biomechanical beam analysis determines certain geometric properties that are direct measures of the mechanical loading placed on the bone in vivo. They reflect the strength and rigidity of bone to resisting gravity and muscle activity. They are therefore indicative of the biological and behavioral characteristics of the individual that produced those loads. In preserved bone, these properties may be used to reconstruct past in vivo types and degrees of physical activities and ultimately the individual's lifestyle (Ruff and Hayes, 1983a; Larsen, 1997).

MATERIALS AND METHODS

Materials

Paired humeri and tibiae of the Cobern Street (CS) skeletal collection were compared to a modern (MS) and a hunter-gatherer (HG) skeletal collection housed in the Department of Anatomy and Cell Biology, University of Cape Town Medical School. These particular long bones were best represented and preserved in this skeletal collection. Table 1 compares the general characteristics of these three samples.

The nature of the Cobern Street cemetery, its unmarked location, and the grave goods suggest that these individuals were either slaves or "free black" people of low socioeconomic standing (Apollonio, 1997; Morris, 1997). The positive identification of at least six of these individuals as slaves or former slaves has been possible, using the combination of evidence from both tooth decoration and dietary reconstruction (Cox, 1999). Age and sex estimates for all these skeletons were determined by Constant and Louw (1997).

Skeletons of the modern sample range in dates of death from 1983–1995. They comprise individuals of "colored" descent classified previously by South African government population criteria. These skeletons probably reflect the descendants of the Cobern Street sample, being representative of a genetically "mixed population." No data are available on the lifestyles of this group. However, it is assumed that these individuals were mainly physically active laborers, since 30 (74% of the sample) are paupers obtained from the local government mortuary (representing a low socioeconomic status), and only 7 of them (23% of the sample)

are bequests. Age and sex were obtained from the cadaver records of this sample.

The hunter-gatherer sample is comprised of skeletal remains with a radiocarbon date between 2,000–4,000 years before present, or undated but associated with a Later Stone Age archaeological context without pottery (Morris, 1992). Selecting the samples from the period before 2,000 years ago excludes pastoralists and early historic groups and limits the economic activity of the people concerned to hunting and gathering. This sample provides us with a prehistoric comparison with a known subsistence strategy and activity pattern. Sex and age were determined according to standard methods using osteological markers.

Methods

The method of biomechanical beam analysis used in this study is detailed and validated by Ruff (1984, 1989). In summary, this analysis determines the strength of a long bone shaft from the amount and distribution of cortical bone measured in a cross section of the shaft that is perpendicular to the long axis of the bone. With the use of an interactive computer graphics software package (known as SLICE and formulated by Nagurka and Hayes, 1980), cross-sectional area properties of long bone shafts can be calculated from photographs of direct bone sections, multiple plain radiography, or computed tomography (CT) bone sections. The latter imaging method has been found to be most accurate and precise (Ruff, 1989), and has been used in this study. A Somatom DRH CT scanner (Siemens, Germany, 1988) was used with display settings of 800H for window setting and 600 H for window width, as recommended by Ruff and Leo (1986).

Maximal length of each bone, measured with the aid of an osteometric board, enabled the accurate determination of the midshaft of each bone. A perspex box was custom-built to ensure that the long bones were perfectly aligned along their midshafts during the scanning procedure. All bones were first positioned with their posterior surfaces resting on this frame. The angle of the CT scanner was varied for each bone scanned, in order to ensure that it was always perpendicular to the bone shaft. The bones were also aligned along the vertical and horizontal beams of the CT scanner. This ensured that true transverse sections of each shaft were taken rather than oblique sections.

Hard-copy films of these bone sections were reproduced with an adjacent 5-cm scale. These hard-copy images were scanned with a telegrapher film scanner (Phillips, Germany, 1996) and stored as JPEG files. These images were then magnified, filtered, and printed onto paper with the use of a computer graphics program. This was done since the hard-copy outputs from the CT scanner were reduced representations of the bony cross sections. The CT images were magnified to double the actual bone size, while the scale from each CT image was kept with its corresponding printed image. This ensured that the magnifications of each printed image could be individually and accurately determined.

A digitizing tablet (Summasketch Plus, Summagraphics Corp., Korea, 1989) was then used to digitize the cortical cross-sectional bone images. The data obtained were analyzed by SLCOMM (Eschman, 1990), a modified, IBM-compatible version of the SLICE program. The geometrical properties generated by this program include (Ruff, 1992):

- The total cross-sectional area of bone shaft (TA; mm^2).
- The total cortical area (CA; mm^2), a measure of the amount of cortical bone in a cross section and an indicator of strength of the long bone diaphysis under pure axial loading.
- Medullary area (MA; mm^2), representing the endosteal area (MA = TA − CA).
- Percent cortical area (%CA) = CA/TA*100, an alternative indication of the amount of compact cortical bone. %CA reflects the relative cortical thickness around an entire cross section (Ruff et al., 1993; Larsen, 1997).
- The second moments of cortical area or inertia; these measure the ability of bone to resist bending forces. They include the maximum and minimum second moments of cortical bone area (Imax and Imin;

TABLE 2. Comparison of maximum long bone length

	Male				Female			
	Tibial length (mm)		Humeral length (mm)		Tibial length (mm)		Humeral length (mm)	
	N	Mean ± SD	N	Mean ± SD	N	Mean ± SD	N	Mean ± SD
Modern sample	18	379 ± 21	18	321 ± 17	11	351 ± 15	13	299 ± 15
Cobern Street	15	360 ± 21	16	304 ± 13	10	344 ± 24	11	290 ± 18
Hunter-gatherer	15	360 ± 21	14	295 ± 22*	14	344 ± 18	15	278 ± 18

* $P < 0.05$.

TABLE 3. Size-standardized mean cross-sectional geometry values for the tibia

	N	TA (mm^2), mean ± SD	CA (mm^2), mean ± SD	MA (mm^2), mean ± SD	IY (mm^4), mean ± SD	IX (mm^4), mean ± SD	J (mm^4), mean ± SD	%CA, mean ± SD	Imax/Imin, mean ± SD
Males									
Modern sample	36	794 ± 119	512 ± 95	281 ± 72	226 ± 60	298 ± 77	524 ± 129	65 ± 7	2.2 ± 0.4
Cobern Street	25	817 ± 154	535 ± 135	281 ± 86	248 ± 111	311 ± 123	559 ± 208	66 ± 10	2.5 ± 0.6
Hunter-gatherer	28	847 ± 116	641 ± 101*	206 ± 72*	220 ± 59	417 ± 126	637 ± 167**	76 ± 8	2.7 ± 0.5*
Females									
Modern sample	23	873 ± 104	473 ± 118	400 ± 119	221 ± 57	301 ± 99	522 ± 141	54 ± 13	2.0 ± 0.4
Cobern Street	20	852 ± 210	494 ± 98	358 ± 152	257 ± 156	275 ± 104	532 ± 224	59 ± 9	2.3 ± 0.5
Hunter-gatherer	29	778 ± 125	517 ± 88	261 ± 125*	164 ± 49*	308 ± 79	472 ± 119	67 ± 12	2.4 ± 0.5***

* $P < 0.05$ for hunter-gatherer vs. Cobern Street and modern samples.
** $P < 0.05$ for hunter-gatherer vs. Cobern Street sample only.
*** $P < 0.05$ for hunter-gatherer vs. modern sample only.

mm^4) and the second moment of area about the X-axis and the Y-axis (IX and IY; mm^4). These are measures of the resistance offered by the cortical bone to bending the bone in an antero-posterior and medio-lateral direction, respectively.

- The polar moment of cortical area or inertia (J = Imax + Imin; mm^4), measuring the bone strength resistance to torsional loads.
- The ratio of Imax/Imin, a measure of the relative maximum bending strength of the bone at that cross section (Ruff, 1987).

Body size standardization

Ruff et al. (1993) determined that cross-sectional geometric properties of bone are related to bone length and indirectly to the size and body mass of the individual. The formulae used for body size standardization are:

1. For cross-sectional area: (area/long bone length^3) $\times 10^8$.
2. For polar moments of area: (I or J/long bone length$^{5.33}$) $\times 10^{12}$.

Computation of humeral asymmetry

Humeral asymmetry was determined to assess the degree of handedness of the three samples. Asymmetry was calculated as the difference between the larger and smaller side divided by the smaller, expressed as a percentage (Trinkaus et al., 1994; Churchill et al., 1995). A value of zero shows bilateral symmetry, and increasing deviation from zero shows higher levels of asymmetry. Humeral asymmetry was determined for bone length, cortical area, and polar moment of area.

Statistical analysis

Results of cross-sectional geometrical properties for each sample were expressed as the mean and standard deviation (SD). Analysis of variance and planned comparisons (least significant difference (LSD) tests) were used to determine the significant differences between the means of the populations. Age data were correlated, using Pearson product-moment correlation, with a number of the bony geometric properties. A significance level of 0.05 was used.

RESULTS

Long bone length differences between the three samples are listed in Table 2. Size-standardized cross-sectional geometric data obtained from the tibia midshafts for each sample are summarized in Table 3, while those for the humeral midshafts are sum-

TABLE 4. Size-standardized mean cross-sectional geometry values for the humerus

	N	TA (mm^2), mean ± SD	CA (mm^2), mean ± SD	MA (mm^2), mean ± SD	IY (mm^4), mean ± SD	IX (mm^4), mean ± SD	J (mm^4), mean ± SD	%CA, mean ± SD	Imax/Imin, mean ± SD
Males									
Modern sample	36	954 ± 159	573 ± 129	381 ± 137	307 ± 94	289 ± 97	592 ± 184	60 ± 12	1.5 ± 0.2
Cobern Street	32	951 ± 163	629 ± 118	322 ± 96	334 ± 139	309 ± 121	647 ± 250	66 ± 9	1.6 ± 0.2
Hunter-gatherer	30	822 ± 168*	616 ± 123	207 ± 102***	228 ± 81*	250 ± 110	478 ± 182**	76 ± 7***	1.5 ± 0.2
Females									
Modern sample	26	929 ± 154	440 ± 123	498 ± 181	242 ± 75	238 ± 78	461 ± 132	48 ± 14	1.7 ± 0.2
Cobern Street	22	870 ± 155	495 ± 93	375 ± 122	244 ± 90	237 ± 88	449 ± 153	58 ± 11	1.6 ± 0.3
Hunter-gatherer	28	772 ± 196*	500 ± 104	271 ± 182***	181 ± 73*	179 ± 74*	375 ± 156	68 ± 16***	1.6 ± 0.2

* $P < 0.05$ for hunter-gatherer vs. Cobern Street and modern samples.
** $P < 0.05$ for hunter-gatherer vs. Cobern Street sample only.
*** $P < 0.05$ for all three samples.

marized in Table 4. Table 5 details the humeral asymmetry values for the three samples. The age correlations with various tibial and humeral cross-sectional geometric properties are shown in Table 6.

DISCUSSION

In comparing these three samples, we are aware of the significantly older mean age for the modern group (Table 1). The mean age of the Cobern Street and hunter-gatherer sample, for both males and females, falls within the fourth decade, while the modern sample falls within the sixth decade. Many of the geometric properties of the bones studied could be expected to show some age-related changes, and therefore differences between the modern sample and the other samples should be interpreted with caution.

Considering the time frame of the three samples, a secular trend was expected. However, there were no significant differences in mean long bone lengths, except for humeral lengths between the male hunter-gatherer and modern samples. A previous study of femoral stature reconstruction showed a significant difference only in males between the Cobern Street and a modern sample drawn from the same cadaver collection as used in this study (Constant, 1999). Despite the absence of a significant result, the greater tibial length in the modern sample in this study compared to the other two groups may indicate a secular trend.

The nutritional status of the hunter-gatherers in this study was assumed to be adequate, based on descriptions of the health of modern !Kung communities of North West Botswana (Marshall, 1976). Little or no evidence of mineral or vitamin deficiency could be found in these groups, and kwashiorkor, edema, and pellagra were absent (Marshall, 1976).

We might have expected to see some decrease in mean long bone length in the Cobern Street individuals due to the reportedly less healthy lifestyle of the slaves of 18th century Cape Town. At the time of enslavement and sale it would be a requirement that slaves be healthy, but the food supply and living conditions on slaving vessels were appalling, and many suffered from

TABLE 5. *Humeral asymmetry values for length, cortical area, and polar moment of area expressed as a percentage*[1]

	Length (%)			CA (%)			J (%)		
	N	Median	Range	N	Median	Range	N	Median	Range
Males									
Modern sample	17	0.6	0.0–1.36	18	6.0	1.2–16.4	18	11.4	0.4–20.3
Cobern Street	11	0.7	0.0–2.0	16	5.5	0.85–29.6	15	10.2	1.5–37.8
Hunter-gatherer	13	2.1	0.6–3.5	15	11.8	3.1–31.6	15	29.6	2.8–62.4
Females									
Modern sample	13	1.4	0.3–2.0	13	5.7	0.2–9.1	13	14.4	3.1–27.5
Cobern Street	8	0.7	0.0–1.9	11	7.4	0.5–24.3	11	10.4	1.7–61.7
Hunter-gatherer	11	1.5	0.0–3.5	14	10.9	2.3–71	14	18.7	0.4–53.4

[1] Asymmetry is calculated as the difference between the larger and smaller side divided by the smaller, expressed as a percentage.

TABLE 6. *Correlation coefficient values (r) for tibial and humeral geometric properties against age*

	Tibial properties					Humeral properties				
	N	TA	CA	MA	J	N	TA	CA	MA	J
Males										
Modern sample	18	0.17	0.1	0.15	0.11	18	0.25	−0.4	0.34	0.17
Cobern Street	13	0.37	0.29	0.24	0.34	16	0.38	0.22	0.36	0.46
Hunter-gatherer	14	0.58*	0.41	0.34	0.66*	14	0.11	−0.6	0.29	0.04
Females										
Modern sample	12	0.19	−0.43	0.59*	−0.3	13	0.35	−0.51*	0.66*	−0.02
Cobern Street	10	0.19	0.63*	−0.14	0.31	11	0.52*	0.21	0.59*	0.45
Hunter-gatherer	14	0.19	0.00	0.25	0.32	14	0.29	−0.4	0.35	0.1

* $P < 0.05$.

disease during the voyage. For slaves in the Cape colony the food supply was variable, with reports indicating that some were inadequately fed (Armstrong and Worden, 1989). Despite these reports, the skeletal evidence of malnutrition, including cribra orbitalia, in the Cobern Street collection is very low (Holtzhausen and Slater, 1997).

Tibiae

Bone areas (TA, CA, %CA, and MA) are proportional to strength in compression and tension when the forces are applied axially. However, most forces applied to long bone diaphyses are eccentric. Second moments of area (Ix, Iy, Imin, Imax, and J) have been found to be more accurate indicators of bone strength and mechanical function (Larsen, 1997). In the male tibiae samples, we found a significant difference between CA and MA between the hunter-gatherers and the other two samples, implying that the hunter-gatherers had stronger tibial shafts to axial loading.

The value for the polar moment of area (J) indicates the amount of torsional loading experienced by bone, while the second moment of area about the X axis of bone cross-sectional areas shows the bending strength of the tibia in the antero-posterior plane. Bending and torsional stresses on the tibia are greatly increased from walking to running (Lanyon, 1982). In groups of active walkers or runners, the tibia shows greater bending stresses in the antero-posterior than the medio-lateral plane due to the pull of the soleus, gastrocnemius, and quadriceps femoris muscles on the shaft (Ruff, 1987). Thus it was no surprise to see the hunter-gatherer sample displaying very high values for J and IX, confirming their very mobile lifestyle. The Cobern Street sample also showed a significant difference from the hunter-gatherer sample for J. The people of the Cobern Street sample appeared to do more walking than the modern group, but much less than the hunter-gatherers. The small differences between the Cobern Street and modern samples may be due to an age effect, with the older individuals of the modern sample doing less activity than the younger individuals of the Cobern Street sample, and to the modern sample doing less walking overall.

Since there is very little medio-lateral loading on the tibia, it is understandable

that no significant difference between the male samples was seen for the IY values. However, the female hunter-gatherer sample shows a significant difference in mediolateral loading from the other two samples. The authors are not certain of how to interpret this finding. Modern female hunter-gatherers have been shown to spend about 6 hours of their day in gathering food. The usual method when digging for roots is described as a posture of squatting or sitting on the ground, with both legs outspread or with one bent and the other spread for balance (Marshall, 1976). This posture may account for this difference seen in mediolateral loading strength.

Both the male and female hunter-gatherer samples are significantly different for Imax/Imin. This ratio is a measure of the relative maximum bending strength of the bone at that level. Ratios greater than 1.0 indicate a more ellipsoidal shape and relate to a greater bending strength in the X or Y planes. The Imax/Imin ratio is indicative of the platycnemic index for the tibia (Lovejoy et al., 1976). Marked platycnemia is an indication of the strength of bones to anteroposterior bending.

Sex comparisons of tibial torsional strength (J) asymmetries show that sexual dimorphism is most marked in the hunter-gatherer sample, less so in the Cobern Street sample, and least marked in the modern sample (Table 6). This concurs with studies (Ruff, 1987; Larsen, 1997) showing that sex differences in the mobility index are greatest in hunter-gatherers, intermediate in agricultural societies, and least in industrial societies. Males tend to be assigned increasingly more sedentary activities with increasing dependence on technology. Sexual division of labor among slave populations at the Cape in the 18th century saw male slaves assigned to work on the farmlands outside and females assigned to do housework activities indoors (Worden et al., 1998).

Peak bone mass in modern populations is reached in the third decade of life and declines thereafter (Ruff, 1992). Cortical thickness and cross-sectional area decrease in both males and females with increasing age, while diaphyseal diameter and subperiosteal area increase (Carlson et al., 1976; Ruff and Hayes, 1982, 1983a,b; Ruff and Jones, 1981). Table 6 shows the marked difference in age-related bone changes between males and females. Modern females exhibit the expected increase of medullary area with advancing age. The hunter-gatherer male sample shows an increase in both TA and J with age, suggestive of the peak bone mass attainment around the early thirties. The fact that hunter-gatherers remain active in their lifestyles right up until death may also contribute to this result.

Endosteal resorption and medullary expansion in individuals that remain active throughout life are compensated for by subperiosteal expansion in order to increase bone strength (Ruff, 1992). Modern U.S. females do not show this compensatory subperiosteal expansion, probably because of a decline in their activity levels and decreasing estrogen levels with increasing age (Ruff, 1992). The modern and Cobern Street female samples show a similar trend to this modern U.S. female population (Table 6).

Humeri

The %CA and the MA were significantly different in both sexes for all groups. While the %CA was greatest among hunter-gatherers and least among the modern group, the pattern was reversed for the MA, which was largest in the modern sample (Table 4). This is in keeping with other studies that have shown smaller medullary areas and greater cortical thickness in more archaic individuals (Pfeiffer and Zehr, 1996; Pfeiffer et al., 1996; Smith et al., 1992). Activity patterns and age may go some way in explaining these differences; however, the genetic composition of the populations may also account for them.

Habitual lifting and carrying of heavy objects require the continual usage of muscles such as the deltoid, latissimus dorsi, and pectoralis major. The values for IY (Table 4) indicate medio-lateral loading of the humerus by these muscles that abduct and adduct the arm. The males from the Cobern Street sample showed the highest values for humeral strength properties (IY and J), attesting to their status as heavy manual laborers. Shell (1997) describes the break-

down of activities that slaves may have been involved in at that time. The majority of male slaves (70%) were involved in manual labor. Slaves worked approximately 10 hours per day except during the plowing and harvesting seasons, when they could be required to work longer hours (Armstrong and Worden, 1989).

Ethnographic studies of San females of Namibia and Botswana show that their gathering activities involved squatting down to dig for roots or pick up nuts, then standing up, picking up loads of already gathered food (and probably a child), moving on to find another root, and squatting to dig again. This activity would be done intermittently over the day. Digging involved the use of digging sticks with slashing strokes at the spot where the stem emerges, both hands on the digging stick, right hand high if chopping toward the left, left hand high if chopping toward the right. Women tended to remove roots easier to dig out and closer to the surface. At the end of a day's gathering, their food loads could weigh up to 20 kg. The women would walk over distances of 5 km or more on these foraging expeditions to return to their campsite (Marshall, 1976; Lee, 1979; Silberbauer, 1981).

Marshall (1976) explains that the !Kung methods of carrying were very effective for their purposes. They were mainly shoulder carriers. The men took all the weight of their loads on their shoulders, and the women distributed their weights between shoulders and hips. In both methods, the bodies of their vertebral columns and the shafts of their lower limb bones were bearing the weight. This may explain some of the high values seen in the hunter-gatherer samples in bone areas, indicative of axial compressive loads on the lower limbs (Table 3). The upper limbs would thus not be involved in carrying these heavy weights for any great distances. As expected, the hunter-gatherer sample had the lowest humeral values for IY in both males and females, and for IX in females (Table 4).

The humeral bending force properties (IY and IX) are significantly different in the hunter-gatherer females but similar between the Cobern Street and modern samples. It is plausible that the domestic chores performed by females in the modern group were very similar to those of the female laborers of the 18th century. Domestic work in the 18th century included scrubbing of floors, churning butter, gardening, and collecting and chopping wood (Armstrong and Worden, 1989).

The results of the bilateral asymmetry of some of the cross-sectional geometric properties of the humerus showed that there was marked lateralization in the hunter-gatherer sample. Their lifestyle probably promoted unilateral upper limb activity patterns such as the use of a bow and arrow or a spear in hunting and an implement in digging (Marshall, 1976). Bilateral asymmetry was less marked in the other two samples. This changing pattern of asymmetry with antiquity has been clearly documented in North America (Larsen, 1997).

Comparisons of sexual dimorphism—the percent side differences between males and females—suggest that both the men and women of the Cobern Street sample were engaged in relatively symmetrical physical activities. The range of bilateral humeral asymmetry found in the modern sample is similar to the moderately high values of asymmetry (~5–14%) found in modern human populations in the U.S. (Ruff, 1992; Trinkaus et al., 1994). Professional tennis players have very high levels of asymmetry (~28–57%), a pattern that is similar to the Cobern Street and hunter-gatherer samples (Table 5). This high level of asymmetry and the overall variability seen in human samples affirm the potential for significant change in bone shaft morphology, depending upon the different mechanical loading of the left vs. the right upper limbs (Ruff et al., 1993, Trinkaus et al., 1994).

In conclusion, this beam analysis study has shown that the hunter-gatherers, with their high mobility, were predominantly involved in activities requiring a greater strength of their lower limbs than of their upper limbs. The Cobern Street sample showed less lower limb activity than the hunter-gatherer sample but considerably more upper limb usage, especially among the male contingent of this sample. The Cobern Street males seemed to be involved in physically demanding tasks of the upper

limbs. As expected, the females showed less upper limb strength than their male counterparts. This could be a reflection of the sex difference found in muscle strength or less likely explained on the basis that they may have engaged in less physically demanding activities. The Cobern Street people appear to have been manual laborers living a more physically demanding lifestyle than their descendants have in the modern group.

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LITERATURE CITED

Apollonio H. 1997. Identifying the dead: eighteenth century mortuary practices at Cobern Street, Cape Town. Paper presented at the 27th Annual Congress of the Anatomical Society of Southern Africa, Cape Town.

Armstrong JC, Worden NA. 1989. The slaves, 1652–1834. In: Elphick R, Giliomee H, editors. The shaping of South African society, 1652–1840. Cape Town: Maskew Miller Longman (Pty), Ltd. p 107–183.

Carlson DS, Armelagos GJ, Van Gerven DP. 1976. Patterns of age-related cortical bone loss (osteoporosis) within the femoral diaphysis. Hum Biol 48:295–314.

Chamay A, Tschantz P. 1972. Mechanical influences in bone remodeling. Experimental research on Wolff's law. J Biomechanics 5:173–180.

Churchill SE, Weaver AH, Niewoehner WA. 1995. Late Pleistocene human technological and subsistence behaviour: functional interpretations of upper limb morphology. Contribution to the International Round Table: Reduction Process ("Chaines Operatoires") for the European Mousterian. Rome.

Constant DA. 1999. Stature and craniometric trends of 18th and 20th century "coloured" adults in Cape Town, South Africa. Perspect Hum Biol 4:167–173.

Constant DA, Louw GJ.1997. Age and sex distribution for the Cobern Street Collection. Paper presented at the 27th Annual Congress of the Anatomical Society of Southern Africa, Cape Town.

Cox G. 1999. Cobern Street burial ground: investigating the identity and life histories of the underclass of 18th century Cape Town. MSc thesis, University of Cape Town.

Eschman PN. 1990. SLCOMM. Albuquerque: Eschmann Archaeological Services.

Goodship AE, Lanyon LE, McFie H. 1979. Functional adaptation of bone to increased stress: an experimental study. J Bone Joint Surg [Am] 61:539–546.

Holtzhausen L-M, Slater CP. 1997. A palaeopathological evaluation of the Cobern Street Collection: a preliminary report. Paper presented at the 27th Annual Congress of the Anatomical Society of Southern Africa, Cape Town.

Jones HH, Priest JD, Hayes WC, Tichenor MA, Nagel DA. 1977. Humeral hypertrophy in response to exercise. J Bone Joint Surg [Am] 59:204–208.

Lanyon LE. 1982. Mechanical function and bone remodeling. In: Sumner-Smith G, editor. Bone in clinical orthopaedics: a study in comparative osteology. Philadelphia: W.B. Saunders Co. p 273–304.

Lanyon LE, Baggott DG. 1976. Mechanical function as an influence on the structure and form of bone. J Bone Joint Surg [Br] 58:436–443.

Lanyon LE, Magee PT, Baggott, DG. 1979. The relationship of functional stress and strain to the process of bone remodeling. An experimental study on the sheep radius. J Biomech 12:593–600.

Larsen CS. 1997. Activity patterns: 2. Structural adaptation. In: Bioarchaeology. Interpreting behaviour from the human skeleton. Cambridge: Cambridge University Press. p 195–225.

Lee RB. 1979. The !Kung San. Men, women, and work in a foraging society. Cambridge: Cambridge University Press. p 310.

Lovejoy CO, Burstein AH, Heiple KG. 1976. The biomechanical analysis of bone strength: a method and its application to platycnemia. Am J Phys Anthropol 44: 489–506.

Marshall L. 1976. Plant foods and gathering. In: The !Kung of Nyae Nyae. Cambridge, MA: Harvard University Press. p 92–123.

Morris AG. 1992. A master catalogue: Holocene human skeletons from South Africa. Johannesburg: Witwatersrand University Press.

Morris AG. 1997. History of the Cobern Street site. Paper presented at the 27th Annual Congress of the Anatomical Society of Southern Africa, Cape Town.

Nagurka ML, Hayes WC. 1980. An interactive graphics package for calculating cross-sectional properties of complex shapes. J Biomech 13:59–64.

Pfeiffer S, Zehr MK. 1996. A morphological and histological study of the human humerus from Border Cave. J Hum Evol 31:49–59.

Pfeiffer S, Lazenby R, Thackery JF. 1996. Tuinplaas: affinity assessed from long bone cross-sectional geometry. Darmstadter Beitrage Naturgeschichte 6:137–143.

Rubin CT, Lanyon LE. 1984. Regulation of bone formation by applied dynamic loads. J Bone Joint Surg [Am] 66:397–402.

Ruff CB. 1984. Allometry between length and cross-sectional dimensions of the femur and tibia in *Homo sapiens*. Am J Phys Anthropol 65:347–358.

Ruff CB. 1987. Sexual dimorphism in human lower limb bone structure: relationship to subsistence strategy and sexual division of labor. J Hum Evol 16:391–416.

Ruff CB. 1989. New approaches to structural evolution of limb bones in primates. Folia Primatol (Basel) 53: 142–159.

Ruff CB. 1992. Biomechanical analyses of archaeological human skeletal samples. In: Saunders SR, Katzenburg MA, editors. The skeletal biology of past peoples: advances in research methods. New York: Wiley-Liss, Inc. p 37–58.

Ruff CB, Hayes WC. 1982. Subperiosteal expansion and cortical remodeling of the human femur and tibia with aging. Science 217:945–947.

Ruff CB, Hayes WC. 1983a. Cross-sectional geometry of Pecos Pueblo femora and tibiae—a biomechanical investigation: I. Method and general patterns of variation. Am J Phys Anthropol 60:359–381.

Ruff CB, Hayes WC. 1983b. Cross-sectional geometry of Pecos Pueblo femora and tibiae—a biomechanical investigation: II. Sex, age, and side differences. Am J Phys Anthropol 60:383–400.

Ruff CB, Jones HH. 1981. Bilateral asymmetry in cortical bone of the humerus and tibia—sex and age factors. Hum Biol 53:69–86.

Ruff CB, Leo FP. 1986. Use of computed tomography in skeletal structure research. Yrbk Phys Anthropol 29: 181–196.

Ruff CB, Trinkaus E, Walker A, Larsen CS. 1993. Postcranial robusticity in *Homo*. I: temporal trends and mechanical interpretation. Am J Phys Anthropol 91: 21–53.

Shell CHR. 1997. Children of Bondage: A social history of the slave society at the Cape of Good Hope, 1652–1838. Johannesburg: Witwatersrand University Press. p 135–171.

Silberbauer GB. 1981. Hunter and habitat in the central Kalahari desert. Cambridge: Cambridge University Press. p 198–200.

Smith P, Horwitz LK, Kaplan E. 1992. Skeletal evidence for population change in the late Holocene of the south-western Cape: a radiological study. S Afr Archaeol Bull 47:82–88.

Trinkaus E, Churchill SE, Ruff CB. 1994. Postcranial robusticity in *Homo*. II: humeral bilateral asymmetry and bone plasticity. Am J Phys Anthropol 93:1–34.

Woo SL, Kuei SC, Amiel D, Gomez MA, Hayes WC, White FC, Akeson WH. 1981. The effect of prolonged physical training on the properties of long bones: a study of Wolff's law. J Bone Joint Surg [Am] 63:780–787.

Worden N, Van Heyningen E, Bickford-Smith V. 1998. Cape Town: the making of a city. Cape Town: David Phillip.